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Climatic diagnostics associated with anomalous lightning incidence during the summer 2012/2013 in Southeast Brazil

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ABSTRACT: The State of São Paulo in Southeast Brazil experienced during the 2012/2013 summer one of the most severe electrical storm events in recent years, causing various impacts to society, e.g. fires and fatalities. Thus, the objective of this work is to understand which mechanisms and climatic variability modes are associated with the lightning incidence during this summer in this region. The study includes a statistical-temporal assessment of cloud-to-ground (CG) lightning occurrence comprising the 16 years period from 1999 to 2014. The results showed that, for this period of analysis, the lightning incidence was associated with climatic patterns connecting the tropical and extratropical region, through a wave train, from the Indian Ocean to South America, favouring the formation and development of convective storms over Southeast Brazil.

KEY WORDS cloud-to-ground lightning; extreme event; São Paulo-Brazil

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1. Introduction

Given the high incidence of cloud-to-ground (CG) lightning in some regions and various types of damage caused by them, scientists around the world have dedicated their research to the understanding of these events. From monitoring periods and areas of greater concentration of electrical activities it is possible to issue alerts of important characteristics such duration and severity of storms, allowing preventive measures to be taken to minimize the impacts (Santos *et al.,* 2016).

For this, analyses of the lightning incidence in diverse time scales of storms have been developed over the years [e.g. Gulf of Mexico, Florida, Archipelago of Indonesia; Austria (Schulz *et al.,* 2005); United States (Schultz *et al.,* 2005); Madagascar and South Africa (Collier *et al.,* 2006); Brazil (Pinto *et al.,* 2006); Gulf Coast (Lajoie and Laing, 2008); Alaska, Canada and United States (Orville *et al.,* 2011); Carpathians (Antonescu and Burcea, 2010); Southwest Indian Ocean (Bovalo *et al.,* 2012); East and Southeast Asia (Yuan *et al.,* 2016) among other studies] in an attempt to understand the processes involved in the occurrence of the phenomenon. Although most lightning have no contact with the surface of the planet (Rakov and Uman, 2003), those that reach the ground can cause expressive damage to structures built by man as well as fatalities. These damages consist of electric systems failures, breakdowns in telecommunications towers and buildings, burning of electronic equipment, among others (Santos *et al.,* 2016), causing damage to society estimated at 500 million dollars a year in Brazil (Pinto, 2005, 2009).

Although the knowledge generated by these studies is of great relevance, there is still a need for the development of more detailed research to identify peculiarities of regions with high concentrations of lightning, as well as the climatic phenomena that modulate them.

Associated with this information, the alert in relation to increase of the frequency of the extreme climatic events caused by the intensification of the global warming, divulged by the *Intergovernmental Panel in Climate Change* – IPCC (2013; 2014) in its latest report, AR5, strengthens the development of research that may point to influences on the formation and development of electrical storms.

Past research has revealed that lightning incidence into the Gulf Coast of Mexico is associated with the occurrence of El Niño Southern Oscillation (ENSO), in which cold episodes (La Niña) resulted in a decrease in lightning incidence, and warm episodes (El Niño), would be associated with an increase in the incidence of the phenomenon (Lajoie and Laing, 2008).

To the southwest of the Indian Ocean, statistical analyses showed that ENSO is the main modulator of the electrical activity, with contribution above 56.8% of the studied events. In this region the Indian Ocean Dipole has an important influence, being able to explain the variability of lightning incidence above 49%, in some regions of

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the southwest Indian Ocean. However, the Madden-Julian Oscillation did not have an expressive impact on the electrical activity on this ocean (Bovalo *et al.,* 2012).

The current literature would benefit greatly from similar studies to those described above for the region of South America, in particular for Brazil. Thus, the objective of this work is to understand which climatic variability modes and dynamic mechanisms are associated to the lightning incidence in a specific region of Brazil, the State of São Paulo, during the summer, focusing on the extreme event occurred during the austral summer (period from December 2012 to February 2013, DJF).

The importance of the development of this type of study for the State is reinforced by São Paulo presenting the highest rates of urbanization and great importance in the economic and social scenario of the Country. The results obtained may serve as a basis for climate forecasting, as well as for the construction and improvement of warning systems, aiming at planning preventive measures to reduce damages to society.

Finally, one of the main justifications for this kind of evaluation is that studies of this nature for this phenomenon in this region are still very incipient. However, it is of great relevance for the understanding and monitoring of the regional climate, and can serve as a scientific basis that can be used to make environmental decisions that minimize the impacts caused by the lightning incidence.

2. Data and methodology

The CG lightning data used in this work for the State of São Paulo, in the Southeast of Brazil come from the Integrated Network for the Detection of Atmospheric Discharges (RINDAT) and the Brazilian Network for the Detection of Atmospheric Discharges (BrasilDAT).

Sixteen years of data were considered, corresponding to the austral summer period from 1999 to 2014, of which the 1999–2010 data are from the RINDAT network and the data from 2011–2014 are from the BrasilDAT network. For the study period, RINDAT showed detection efficiency above 80% and BrazilDAT above 90% (Naccarato and Pinto, 2009; Bourscheidt *et al.*, 2014). These values indicate that both networks had full conditions to use their data. The networks detect the electromagnetic pulse from a lightning strike and calculate latitude and longitude of the point of incidence, time of occurrence in UTC, among other characteristics.

The temporal series was analysed with the objective of evaluating the behaviour of the lightning incidence during the quarter of DJF along the years, analysing possible trends and highlighting the extreme event.

To analyse the trend of the observed data, we used the non-parametric Mann-Kendall statistical test. This method was used because it does not require a normal distribution (Gaussian) of the data series, which is a characteristic of lightning data, and also due to its result being less influenced by outliers values, as, its calculation is based on the sign of the differences, not directly in the variable values.

Originally created by Mann (1945) and reworked by Kendall (1948), the test consists of comparing each value of the data series with the subsequent values, calculating the number of times that the remaining terms are greater than the analysed value. The nonparametric test is used to analyse the existence of a monotonically increasing or decreasing trend and is the most appropriate method to analyse climate change in climatological data series (Goossens and Berger, 1986). The statistical Mann-Kendall is determined as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{VAR}(S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \frac{S+1}{\mathrm{VAR}(S)} & \text{if} \quad S < 0 \end{cases} \tag{1}$$

on which,

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sign}\left(x_j - x_k\right) \tag{2}$$

where x_j and x_k are values (annual/seasonal/monthly) in years j and k (to $j > k$), respectively; n is the size of the data series; and the sign function is the variance S, denoted by [VAR(S)], assumes the value 1 when $x_j - x_k > 0$; 0 when $x_j - x_k = 0$; and −1 when $x_j - x_k < 0$, and it is defined by:

$$\mathrm{VAR}\,(S) = \frac{n\,(n-1)\,(2n+5)}{18} \tag{3}$$

And when there is data repetition, the variance takes the expression:

$$\mathrm{VAR}\,(S) = \frac{1}{18}\left[n\,(n-1)\,(2n+5) - \sum_{p=1}^{g}\left(t_p - 1\right)\left(2t_p + 5\right)\right] \tag{4}$$

where g is the number of groups of repeated data, and t_p is the number of data in the p-th group. For trend analysis using the value of Z in which the positive ($Z > 0$) refers to a rising trend and the negative value ($Z < 0$) refers to a decreasing trend.

Was also estimated the slope and magnitude of the trend from the observed data of lightning, using the Sen's non-parametric method (Sen, 1968; Sneyers, 1975). The method uses a linear model to estimate the slope of the trend and residual variance, being constant in time. The test was used because it is insensitive to the values of outliers, providing a more realistic measure of the trends in a time-series data, which makes it more stringent than usual linear regression. The method is determined by:

$$f\,(t) = Qt - B \tag{5}$$

where Q is the value for the slope and B is a constant.

For the estimation of Q slope first calculates the inclinations of all data pairs, defined by:

$$Q_i = \frac{x_j - x_k}{j - k} \tag{6}$$

to $j > k$.

If the time series is comprised of n values x_j, are obtained $N = n(n-1)/2$ slope estimates Qi. Thus, the slope estimated by Sen's method is the median of N values of Qi, which are sorted in ascending order and are given by Sen's estimate:

$$Q = Q_{[(N+1)/2]} \quad \text{if } N \text{ is odd , and}$$

$$Q = \frac{1}{2}\left(Q_{[N/2]} + Q_{[(N+2)/2]}\right) \quad \text{if } N \text{ is even} \qquad (7)$$

To obtain an estimate of B in Equation (5) are considered n difference values $x_i - Q_{ti}$.

To classify extreme cases, with the objective of characterizing the events with the highest occurrence of discharges, the technique of percentiles (quantile) was used as proposed by Pinkayan (1966). Widely used by Santos *et al.,* 2016, this technique is based on the cumulative frequency distribution, in which the approximation of the probability density function describing the phenomenon is better when the number of observations available is higher. The ranges for each percentiles represent the probabilities or expected frequencies for each of the events that may occur following the time series of a variable x. This methodology consists strictly on the distribution in an ascending order of a continuous sample series, being assigned a probability p univocally each sample value (Xavier, 1999, 2002) – in this work, the series is comprised of the total CG lightning observed in the summer. Thus, the time series can be distributed as $\{x1, x2, x3, ..., xn\}$, in which $x1$ is the lowest value and xn the highest. The index n thus represents the sample size. Finally, the quantiles are calculated and, in this particular case, percentiles, since division takes 100 shares. Afterwards, the quantile orders and classification in itself groups are obtained (Lopes *et al.,* 2013). This study used the quantile order $Q0{,}85$ to establish the class 'extreme' in relation to the observed values (xi) CG lightning.

The method of percentiles allows you to select objectively and quickly anomalous weather events of interest to study a given period. It is noteworthy that, in the quarter calculation DJF the first year study (1999) were considered only the months of January and February, since the discharge of data recorded in December 1998 was not included in the database. In the analysis of the results it was evident that the use of only 2 months, did not change the outcome of the class for this quarter, since in 1999 the number of lightning of this quarter was very close to that observed in the following years.

For the analysis of the climatic patterns associated with the occurrence of lightning, were used reanalysis data available on the National Oceanic & Atmospheric Administration (NOAA) site of the variables of sea surface temperature (SST), geopotential height at the levels of 850 and 200 hPa, specific humidity, zonal and southern wind components, outgoing longwave radiation (OLR), streamfunction, velocity potential and precipitation.

For the fields of streamfunction and velocity potential was used the sigma level of 0.2101 representing the top of the troposphere. In addition, for a punctual analysis of the observed rainfall volume, was used precipitation data from the National Institute of Meteorology (INMET).

The understanding and interpretation of the dynamic mechanisms associated to the lightning incidence was based on the analysis of spatial correlation between the analysed fields and the data series of lightning.

3. Results

The time series of lightning in the austral summer (DJF) from 1999 to 2014 is shown in Figure 1. It can be observed that the lightning events that occurred between the beginning of the series (1999) and the year 2009, generally, presented a value around the average of 323.19 discharges per summer, and the most representative events occurred after 2009, with expressive values in the years 2010 and 2013 (Figure 1(a)). The application of the percentile method identified this last year as an extreme event. These results pointed to an increasing trend in lightning incidence, with magnitude of +6700 lightning year^{-1}, statistically significant at the 10% level.

Figure 1(b) shows the time series of relative deviations from the monthly historical average (in percentage) of the number of lightning in the summer months. In this figure, it is possible to observe the high magnitude of the event of 2013 in relation to the others. The months with the highest lightning incidence at this event, December 2012 and February 2013, showed deviations of approximately 150 and 200% above normal, respectively. Already the month of January 2013 presented a below-average lightning incidence, with deviations of around 10% below normal.

Figure 2 shows the spatial field of anomaly of atmospheric discharges in the quarter of DJF (Figure 2(a)), and separately in the months of this quarter, December 2012 (Figure 2(b)), January (Figure 2(c)) and February 2013 (Figure 2(d)). It is observed that DJF showed positive anomalies of lightning over practically the entire State, mainly on the northeast of São Paulo, which registered a density anomaly above 2.0 flashes km^{-2}.

In the monthly analysis, the highest discharge density was observed in the months of December 2012 and February 2013, as observed in Figure 1(b). In January, it was a month that presented below-average discharge density (with values above −2.0 flashes km^{-2}). It is observed that both the highs recorded in December and February, and the minimum recorded in January, occurred in greater proportions over the capital and Metropolitan Region of São Paulo (MRSP – 23°S/46°W), that is, during the period with positive anomalies (DJF, December and February), there was a large concentration of lightning on the MRSP and in January the maximum negative anomaly was also observed on MRSP.

The high lightning incidence observed in this event, caused great impacts to the population, as in the city of Ourinhos, in the interior of the State, where a lightning strike caused a fire in a reservoir, with almost five million litres of fuel. In Bertioga, on the coast of São Paulo, the lightning incidence resulted in two fatalities, when struck by lightning as they left the beach. In the capital, São

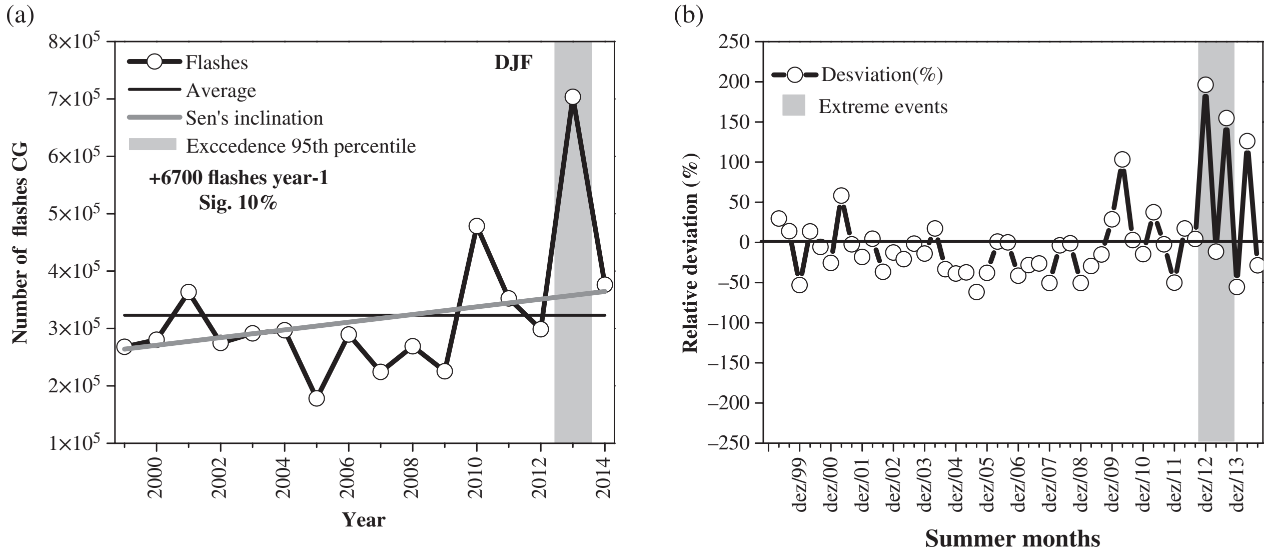

Figure 1. Time series of the observed lightning in the State of São Paulo, comprising the period from 1999 to 2014, considering: (a) totals number of flashes in the quarter of DJF; and (b) relative deviations around the 1999–2014 mean (in percentage) of summer months. The grey hatching area highlights the 2013 extreme event.

Paulo, there were daily records above 2000 flashes, in the month of February. These facts highlight the great power of destruction and the impact caused by extreme events of discharges.

4. Large-scale dynamics

Due to the high concentration of lightning registered in the quarter of DJF 2012/2013, and due to the impacts that the incidence of this phenomenon caused in this event, and may cause in other cases, this section is dedicated to investigate the relationship between lightning in the State of São Paulo and large-scale oceanic and atmospheric patterns, in order to determine possible climatic mechanisms associated to the increase in the lightning incidence in São Paulo, with special attention to the extreme event of summer 2012/2013.

The SST is generally considered as a key parameter for the understanding of climatic anomalies (Coelho *et al.,* 2016). Thus, Figure 3(a) shows the simultaneous correlation between lightning observed in the quarter of DJF in the State of São Paulo (average in all the State) and the SST in the period from 1999 to 2014.

A pattern of oscillation between positive and negative correlations is observed on the southern Indian, Pacific and Atlantic Oceans. Negative values of correlation represent oceanic regions with negative association between SST and the lightning incidence on São Paulo. That is, there is consistency of anomalously cold oceanic conditions with the increase in the lightning incidence on São Paulo, and of anomalously warm ocean conditions with the decrease of lightning. On the other hand, positive correlation values indicate a positive association between SST and the lightning incidence on São Paulo. That is, there is consistency of anomalously warm ocean conditions with the increase in the lightning incidence, and anomalously cold oceanic conditions with the reduction of the number of lightning over the State of São Paulo.

On the Indian Ocean, southeast of the African continent, the Pacific Ocean, eastern Australia and the South Atlantic, around 60°S, negative correlation values are observed. Over the Indian Ocean, adjacent to the west coast of Australia, over the South Pacific, around 50°S, and at approximately 60°S/10°W above the Atlantic, a pattern of positive correlations is observed. This oscillation between positive and negative correlations can be considered as indicative that during the period of 16 years (1999–2014), the variability of the Indian, Pacific and South Atlantic oceans explained the dynamics of lightning on the State of São Paulo.

In this oscillation, the great oceanic areas with correlation of opposite signs on the east of the South Pacific Ocean and the west of the South Atlantic stand out, forming a species of east–west gradient. Fraedrick and Lutz (1986) also identified an east–west dipole on oceanic regions near them, appointed teleconnection of South America, which is configured as part of the Pacific South America pattern (PSA), which connects the tropical region of Indonesia/Pacific with South America (Mo and Ghil, 1987; Ghil and Mo, 1991; Mo and Paegle, 2001).

Also in this figure, the correlation between the atmospheric lightning and the geopotential height field in the 850 hPa level (contours) in the summer quarter (DJF) between 1999 and 2014 is shown. A positive correlation pattern is observed over the eastern Pacific Ocean, showing a consistent association of increase (decrease) of atmospheric pressure on the ocean and increase (decrease) in the lightning incidence over the State of São Paulo.

The opposite association occurs on the west of the South Atlantic Ocean, to which it presented a negative correlation pattern, showing a consistent association between the increase (decrease) of the atmospheric pressure on this

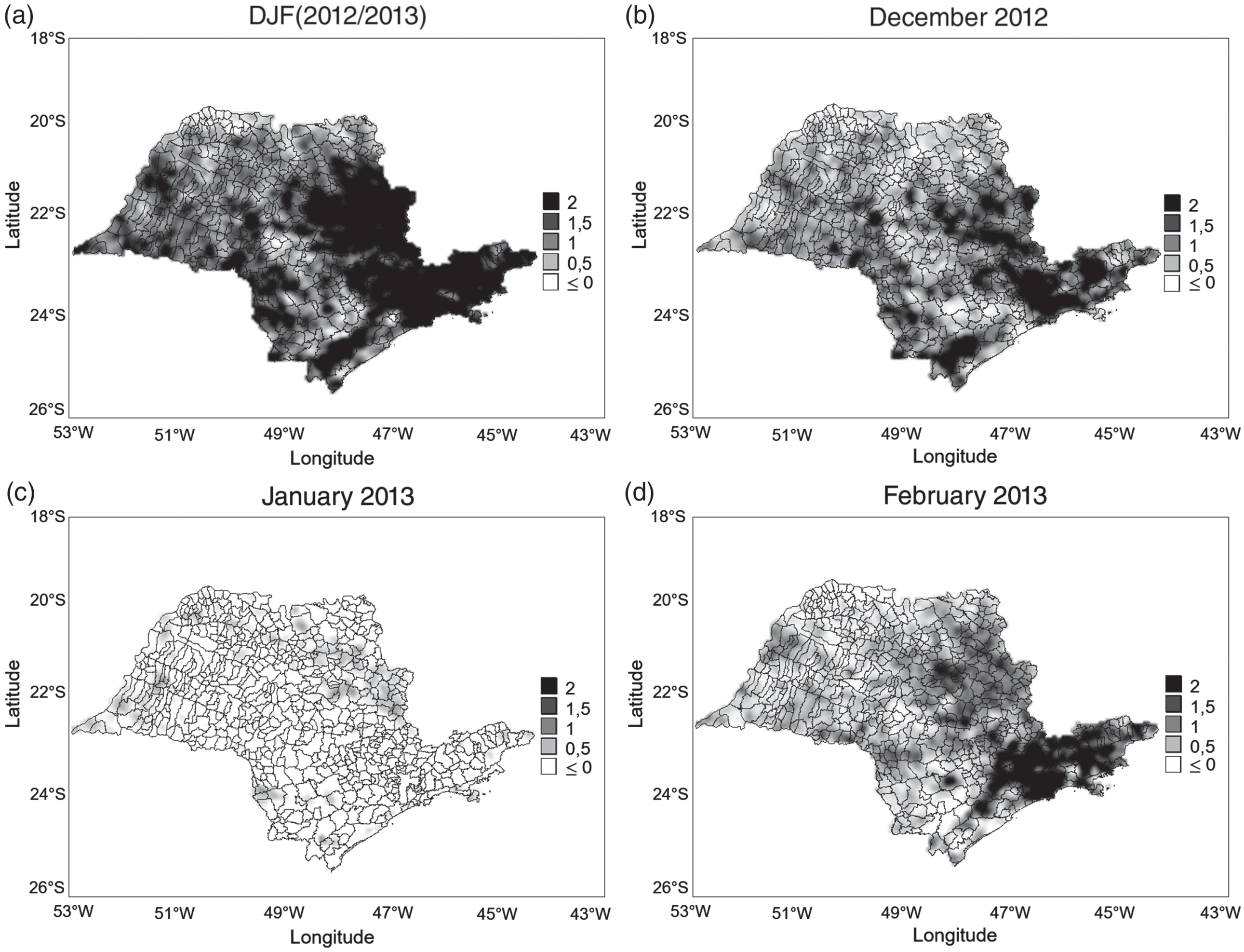

Figure 2. Lightning density anomaly (flashes km^{-2}) during the 2013 summer, considering: (a) DJF; (b) December 2012; (c) January 2013 and (d) February 2013. Anomalies were computed with respect to the 1999–2014 period.

ocean and the decrease (increase) in the lightning incidence on the State.

These results may be indicative of a possible relationship between the southern regions of the Pacific and Atlantic oceans and lightning observed over the State of São Paulo.

Figure 3(b) shows the observed field of SST anomalies and geopotential height (850 hPa) in the DJF quarter of 2012/2013. Negative SST anomalies are noted between −0.5 and −2.0 °C over the Indian Ocean, southeast of Africa, over the central Pacific (around 30°S/130°W) and over the Atlantic South. This oceanic pattern is consistent with the correlation pattern of Figure 3(a), which indicates that cold oceanic conditions over these regions are associated with an increase in the lightning incidence over the State of São Paulo.

Figure 3(b) also shows positive SST anomalies over the Indian Ocean, adjacent to the west coast of Australia, over the South Pacific at approximately 60°S and southwest of the Atlantic Ocean, around 35°S/01°E. This pattern is also in agreement with the correlation pattern of Figure 3(a), which shows that warm ocean conditions on these regions are associated with an increase in the lightning incidence over the State of São Paulo.

In the anomaly field of 850 hPa (Figure 3(b)), positive anomalies were observed over New Zealand and east of the Pacific Ocean, as well as over the South Pacific, adjacent to south-western South America. This pattern is consistent with the correlation pattern shown in Figure 3(a), which shows a positive association between the increase in atmospheric pressure in these regions and the increase in the lightning incidence over São Paulo.

Figure 3(b) also shows that the inverse pattern, this is, negative anomalies of the geopotential height, showing that the atmospheric pressure was below normal, was observed on the South Atlantic Ocean, a pattern that is also consistent with the correlation pattern of Figure 3(a) that indicates a negative association between geopotential height over this region and lightning, indicating, therefore, favouring the lightning incidence on the State.

In the monthly analysis (Figures 4(a)–(c)), it was verified that, in relation to SST, the observed pattern was similar to that of the quarter of DJF, however, in December there were anomalously warm temperatures on the Atlantic Ocean, adjacent to the coast South and Southeast Brazil (Figure 4(a)), which, according to the positive association relation shown in Figure 3(a), favours the lightning incidence on the State of São Paulo, because the elevated SST

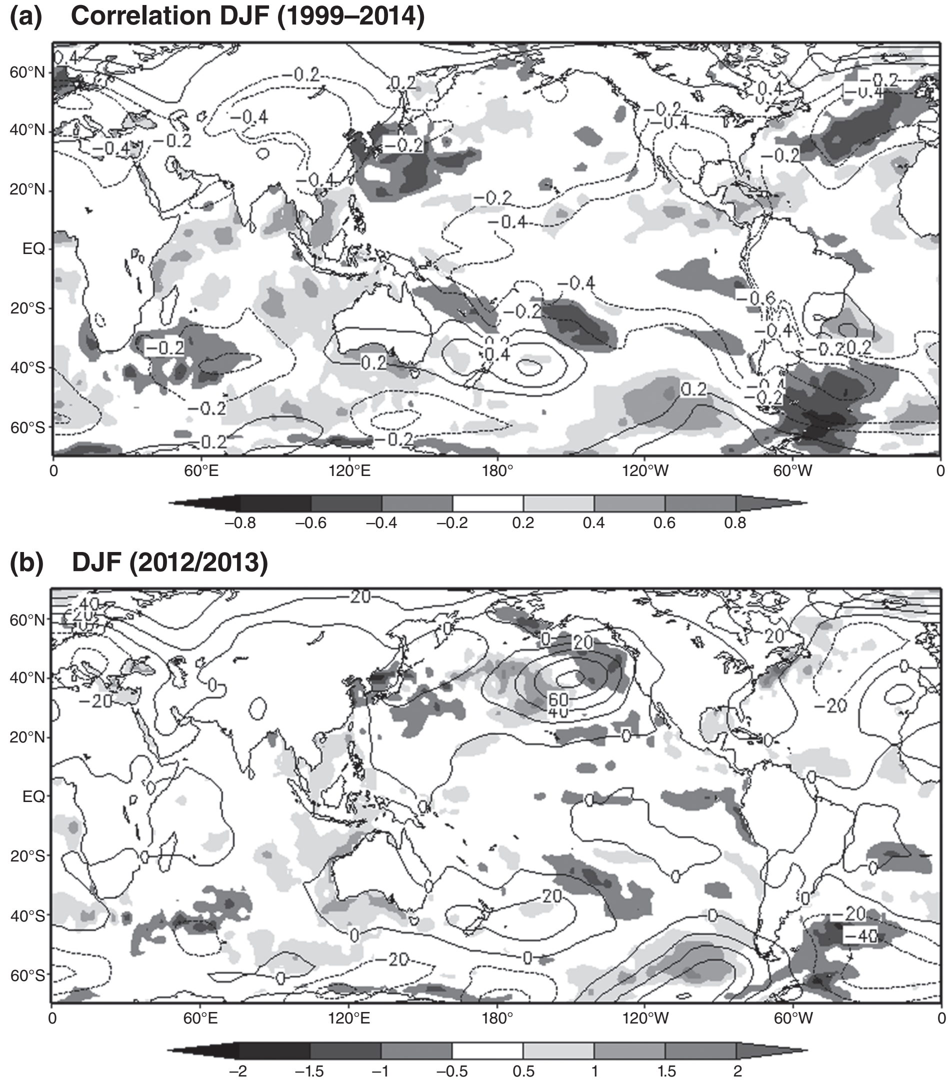

Figure 3. (a) Simultaneous correlation between observed lightning in the State of São Paulo and SST (shaded) and between lightning and 850 hPa geopotential height (contours) during the quarter of DJF for the period 1999–2014; (b) observed SST anomalies (shaded) and 850 hPa geopotential height anomalies (contours) in the quarter of DJF. Anomalies were computed with respect to the 1981–2010 period.

favours evaporation and results in the favouring the formation and development of clouds on the State of São Paulo. In the geopotential height field, the areas with anomalies were more elongated around 60°S, but with the same signal as observed in the quarter.

Figure 5 shows the anomalous fields of specific humidity and circulation at the 850 hPa level for the DJF quarter, and in the months separately for this quarter: December, January and February. In the DJF (Figure 5(a)), on the east of the South Pacific Ocean and west of the South Atlantic Ocean, anomalies of the circulation were observed, with anti-cyclonic anomaly and cyclonic anomaly, respectively. An anomalous anticyclone is also observed on oceanic areas east of New Zealand. These configurations are in agreement with the anomalies of the geopotential height field shown in Figure 3(b) that also highlight these same centres of anomalous circulation. In the field of specific humidity, there are positive anomalies around 2.0 g kg^{-1} on areas of the Amazon and towards the South and Southeast of Brazil.

In December 2012 (Figure 5(b)), the anomalies of cyclonic circulation over the west of the South Atlantic were elongated, covering the South of South America and the Pacific adjacent to the west coast of South America. In addition, there are anomalous winds from the equatorial region towards the South and Southeast of South America, which favoured the transport of moisture from the Amazon to this region. This observed configuration may be associated to the Low Level Jet (LLJ), which causes the flow of moist air from the Tropical Atlantic Ocean, passing through the Amazon region towards the South/Southeast of Brazil and northern Argentina, channelled through the Andes Cordillera acquiring a greater amount of moisture due to the high evapotranspiration of the forest, feeding the convective systems that occur in these regions, e.g. South Atlantic Convergence Zone and Frontal Systems (Marengo, *et al.*, 2004).

In January of 2013 (Figure 5(c)), the wind direction from the equatorial region was modified, restricted to the Brazilian Northeast, which caused this month was not

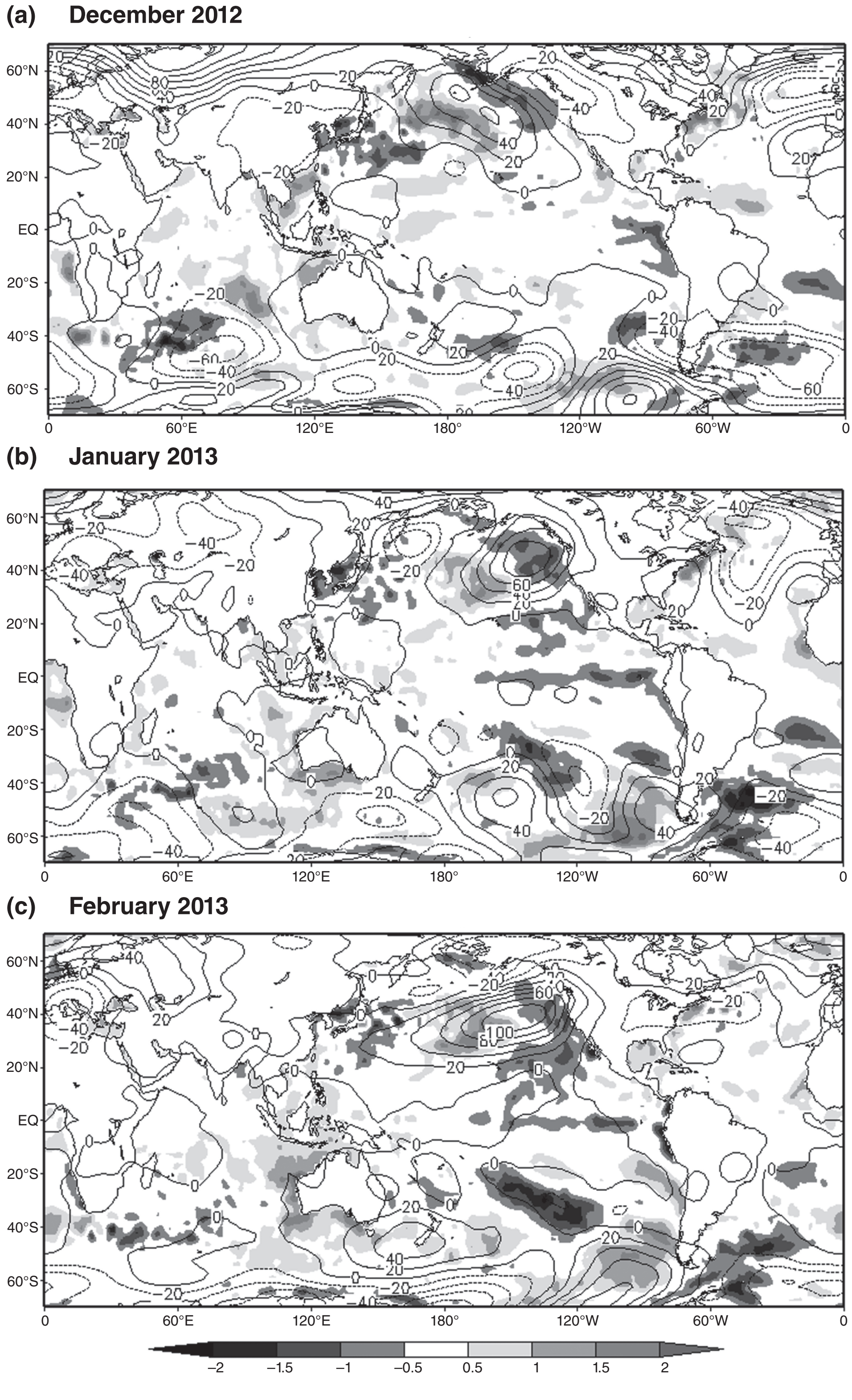

Figure 4. Observed SST anomalies (shaded) and 850 hPa geopotential height anomalies (contours) in (a) December 2012; (b) January 2013; and (c) February 2013. Anomalies were computed with respect to the 1981–2010 period.

observed the humidity above the normal on the region in study. In February (Figure 5(d)), the anomalous circulation returned to orientate in the northwest/southeast direction of South America, and the specific humidity values returned to be higher than normal over the South/Southeast of Brazil.

Figure 6(a) shows the simultaneous correlation between lightning, outgoing longwave radiation (OLR) and geopotential height at 200 hPa level for the DJF quarter in the period 1999–2014. The correlation between the geopotential height and lightning shows that there is a positive correlation on the south of the Pacific Ocean, negative on

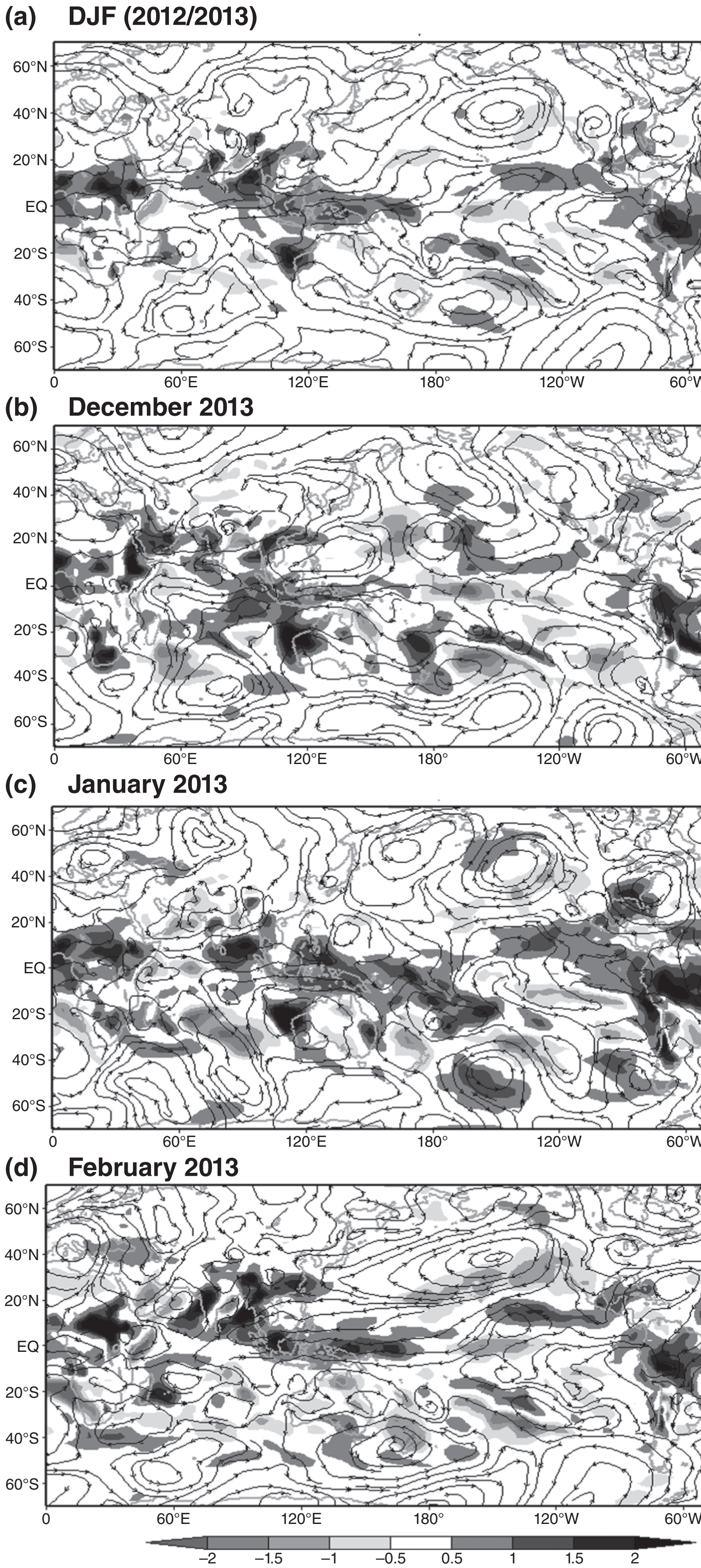

Figure 5. Specific humidity (shaded) and atmospheric circulation (contours) anomalies in the 850 hPa level, considering: (a) DJF quarter; (b) December 2012; (c) January 2013; and (d) February 2013. Anomalies were computed with respect to the 1981–2010 period.

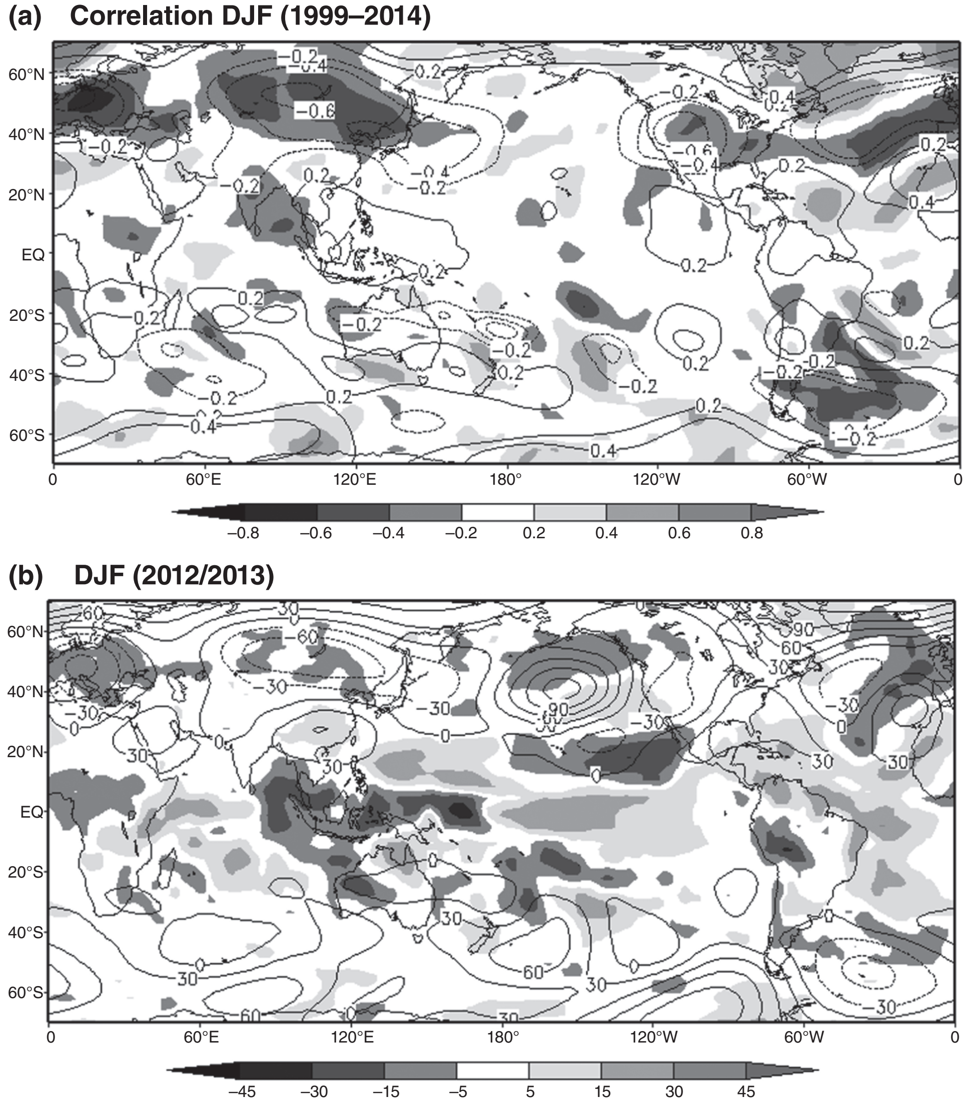

Figure 6. (a) Simultaneous correlation between lightning observed in the State of São Paulo and outgoing longwave radiation (OLR – shaded) and 200 hPa geopotential height (contour) during the quarter of DJF for the period 1999–2014; (b) observed OLR and 200 hPa geopotential height anomalies in the quarter of DJF. Anomalies were computed with respect to the 1981–2010 period.

the south of South America and the Atlantic Ocean and positive on the south-central of South America, suggesting the performance of a wave train pattern, connecting the South Pacific and Atlantic oceans and the lightning incidence over the State of São Paulo.

In the OLR field, the negative correlation between the South and South-East of South America and the west of the South Atlantic Ocean is highlighted, that is, when OLR is below normal (associated with convection and cloudiness) favourable conditions are the increase in the incidence of lightning over São Paulo, and when OLR is above normal (associated with the downward movement and clear sky) favourable conditions for the reduction of the lightning incidence. The opposite correlation pattern, that is, positive correlation, occurs over part of the Northeast of Brazil and the Tropical Atlantic. These inverse correlations exhibit a dipole pattern, which may produce variations in the intensity and location of the South Atlantic Convergence Zone (SACZ) (Grimm and Zilli, 2009; Grimm, 2011).

In the analysis of these fields observed in the summer of 2013 (Figure 6(b)–7(c)), it can be observed that the anomaly of the quarter of DJF presented the values of atmospheric pressure above the normal on the east of the South Pacific and below the normal one on the west of the Atlantic Sul, which is in accordance with the correlation pattern shown in Figure 6(a) in relation to the increase in the incidence of lightning on the State of São Paulo. However, in the average of the quarter anomalies were not identified on the Southeast of Brazil, as in Figure 6(a). It was only possible to identify anomalies when analysing this field in monthly scale (Figure 7(a)–(c)). In December 2012 (Figure 7(a)), above normal atmospheric pressure anomalies were observed over south-central South America, in accordance with Figure 6(a), reproducing the propagation of the wave train in this event. In January of 2013 (Figure 7(b)), this pattern was not as configured as in the previous month, and in February (Figure 7(c)), although the areas and the intensity of these anomalies

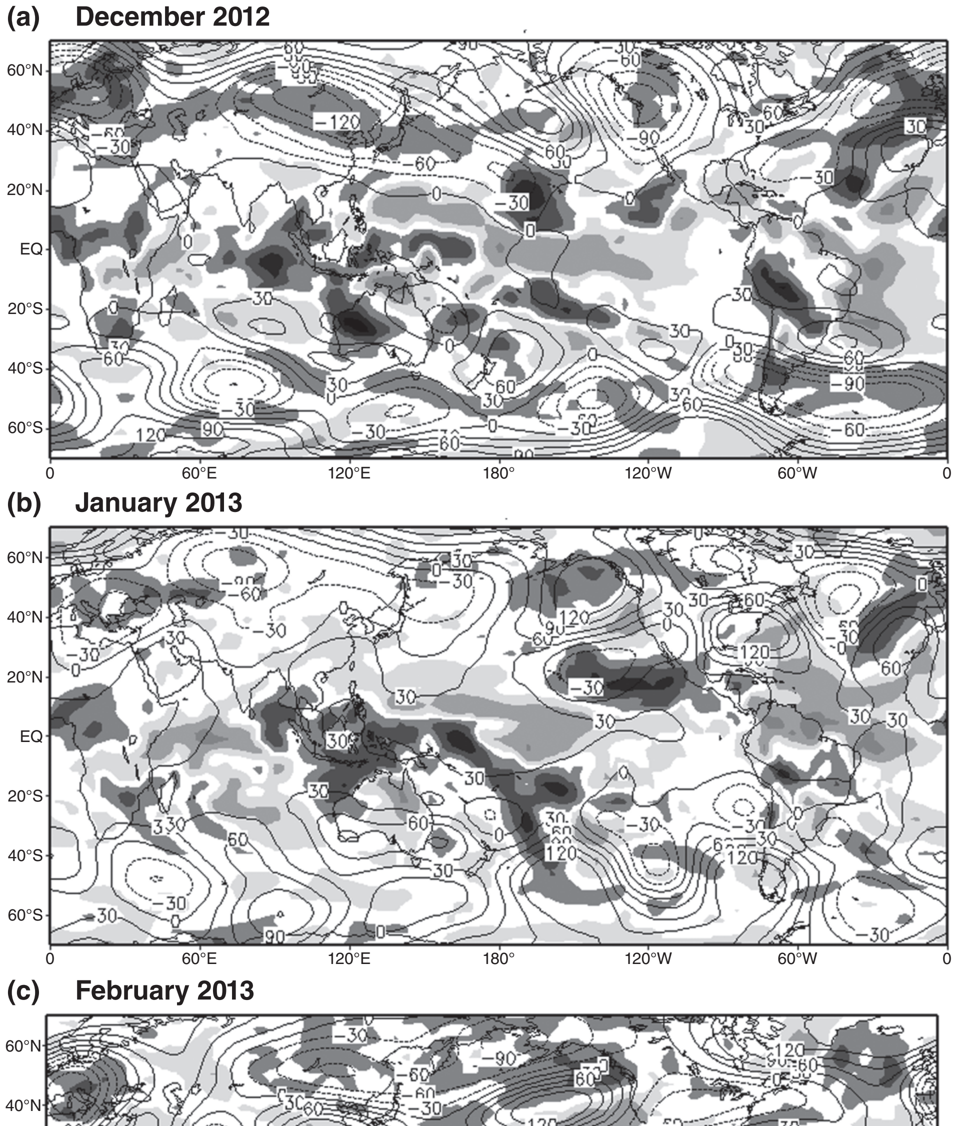

Figure 7. Observed OLR and 200 hPa geopotential height anomalies in (a) December 2012; (b) January 2013; and (c) February 2013. Anomalies were computed with respect to the 1981–2010 period.

were smaller, the variation between positive and negative pressure anomalies was present.

In the OLR anomaly field, the mean of the quarter did not allow to observe abnormalities on the Southeast of Brazil, since, in spite of the cloudiness observed in December and in lower intensity in February, the month of January presented positive OLR anomalies, resulting in a mid-quarter field within the normal range. The month of December was characterized by the presence of more intense negative anomalies, with a northwest/southeast orientation of South America, from an Amazon to the South/Southeast of Brazil, which may be associated with the SACZ. In February, this pattern was not as well configured nor as intense as in December, however, negative anomalies of OLR

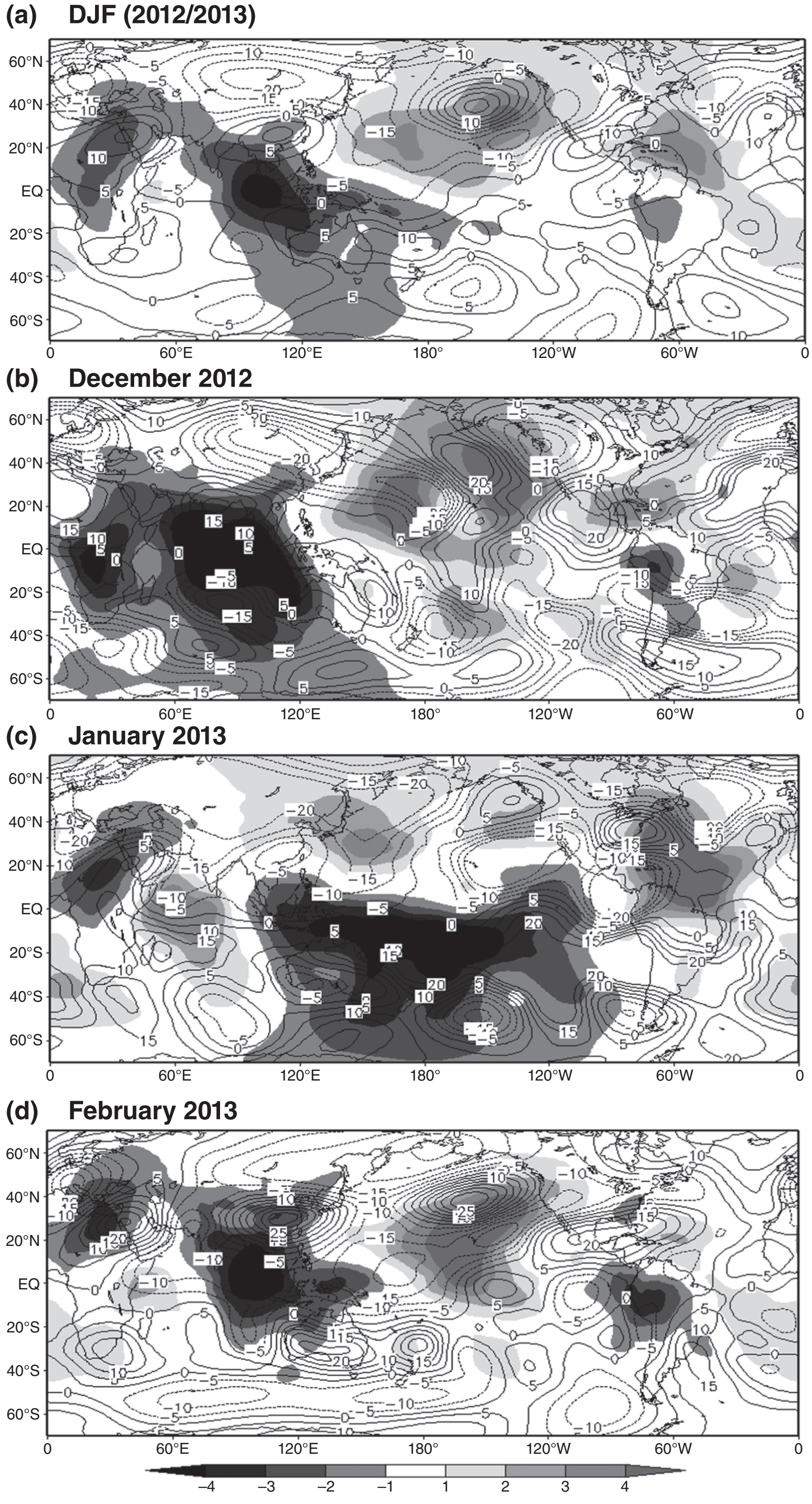

Figure 8. Streamfunction (contours) and velocity potential (shading) anomalies at the top of the troposphere, considering: (a) DJF quarter; (b) December 2012; (c) January 2013 and (d) February 2013. Anomalies were computed with respect to the 1981–2010 period.

between South/Southeast Brazil and the Atlantic Ocean were also observed. This configuration is in accordance with the lightning incidence in this event, which was above average in the months of December and February (the latter in lower intensity) and below the average in January.

Figure 8 shows the fields of streamfunction and velocity potential anomalies in the upper troposphere. Through the streamfunction anomaly, which represents the rotational component of the atmospheric flow (Coelho *et al.*, 2016), is highlighted the wave train headed from the Indian Ocean

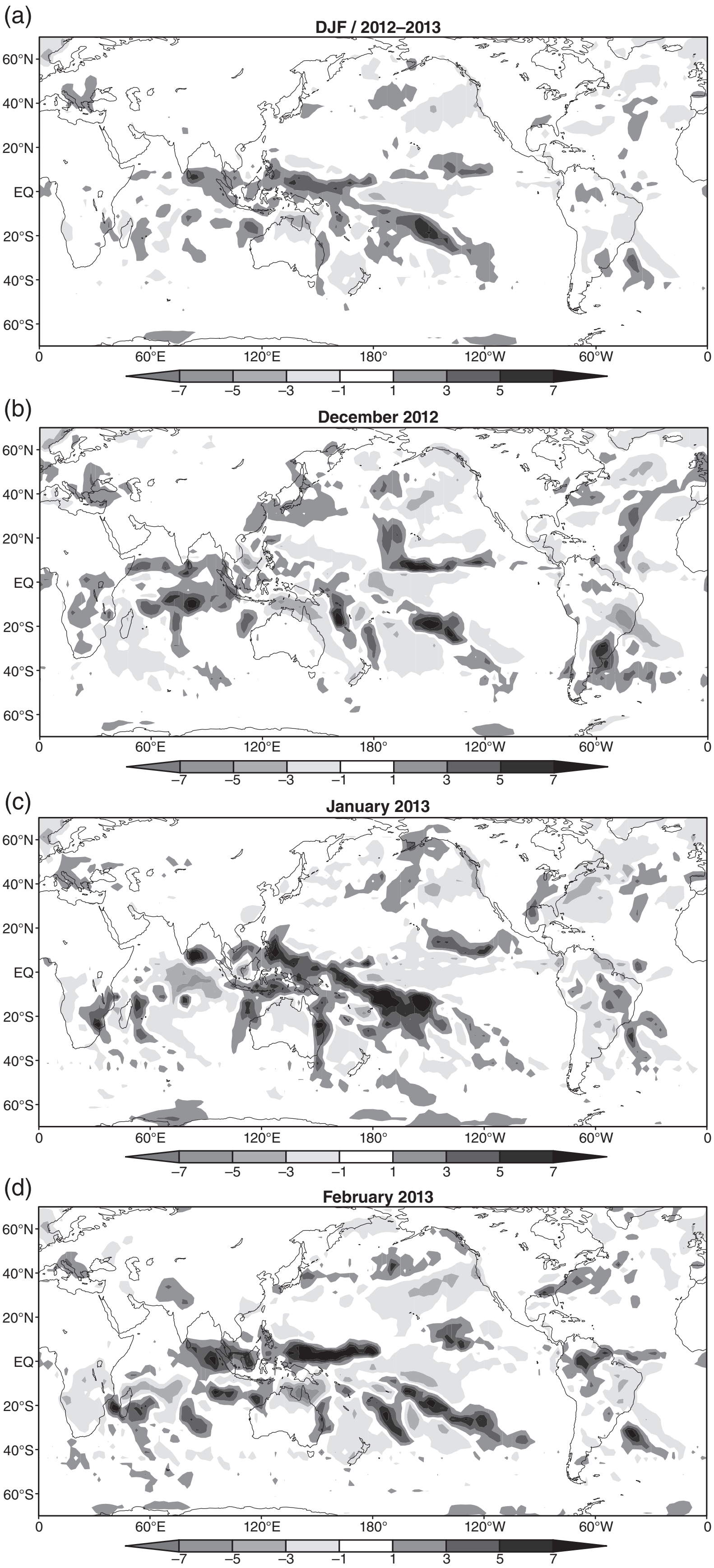

Figure 9. Precipitation anomalies (mm day^{-1}) considering: (a) quarter of DJF; (b) December 2012; (c) January 2013 and (c) February 2013. Anomalies were computed with respect to the 1981–2010 period.

to South America, mainly in DJF (Figure 6(b)) and in December 2012 (Figure 7(a)), as mentioned in the geopotential height anomaly field (Figures 6 and 7).

In the velocity potential anomaly field, which represents the non-rotational component of the atmospheric flow (Coelho *et al.*, 2016), it was observed that in the months of December 2012 (Figure 8(b)) and February 2013 (Figure 8(d)) the altitude divergence, represented by the negative values of velocity potential, indicated that at lower tropospheric levels there was convergence, and consequent favouring of cloud formation and development, in a northwest/southeast configuration, from the Amazon region to the Southeast of South America and the adjacent Atlantic, which is consistent with the pattern OLR anomaly, shown in Figure 7.

Figure 9 shows the precipitation anomalies for the study period (mm day^{-1}). As in the analysis of outgoing longwave radiation anomalies, the mean of the DJF quarter did not present rain anomalies over the study region, however, in the monthly analyses, it is possible to visualize positive anomalies in December over South and Southeast of the South America (Figure 9(b)), and in February concentrated in a small area of Southeast of the South America (Figure 9(d)).

The data observed in surface meteorological stations have shown that in some cities of the state, e.g. São Carlos, Sorocaba Campos do Jordão, São Carlos, Franca and Votuporanga, presented above normal rainfall volumes, mainly in the month of December over the capital São Paulo (figure not shown).

5. Conclusions

This study investigated of one of the most severe lightning events recorded in the last years over the State of São Paulo, in the Southeast Brazil, which occurred during the 2012/2013 austral summer, aiming to understand the mechanisms and modes of climate variability associated with lightning incidence during the summer in this region. Based on CG lightning data between 1999 and 2014, the study also included a brief statistical-temporal assessment of the occurrence of this phenomenon.

In the analysis of the modes of climate variability, positive and negative oscillations between lightning and SST correlations were identified in the Indian, Pacific and South Atlantic Oceans, which can be considered as indicative that during the 16-year period investigated the SST variability in these oceans was associated with the dynamics of lightning over the State of São Paulo.

In the geopotential height fields, circulation and streamfunction, it was possible to observe the influence of a wave train pattern, connecting the region of the Indian Ocean to South America. The OLR, specific humidity and velocity potential analysis revealed favourable (and associated) patterns to cloud formation on the area under study, especially in December 2012 and February 2013, months that recorded the highest lightning incidence of this event.

Specifically on the eastern South Pacific Ocean and the western Atlantic Ocean, the atmospheric and oceanic fields analysed were representative of correlations with the phenomenon under study, which may be indicative of a possible relationship between the southern regions of the Pacific and Atlantic Oceans and the observed lightning over the State of São Paulo. For the period under study, there was a tendency for increasing the incidence of this phenomenon, with a magnitude of +6700 flashes year^{-1}.

In view of the above, this study contributed to advance the knowledge of the mechanisms associated with high lightning incidence observed during the 2012/2013 summer over São Paulo State, and can guide future related studies on this subject, as well as support building knowledge about climatic variability modes that influence the pattern of occurrence of this phenomenon in the investigated region.

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